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Radiological Dose and Health Risk Assessment of Naturally Occurring Radioactive Materials at Kataeregi Artisanal Mining Site, Niger State Using RESRAD Code

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ABSTRACT
This study examined the distribution of naturally occurring radioactive materials (NORM) and the corresponding gamma radiation exposure in Kataeregi artisanal mining area of Niger State, Nigeria. To assess radioactive exposure and possible health hazards, a combination of experimental measurements and RESRAD modeling was used. Activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K were found to be 18.74±0.8, 9.12±1.23 and 360.13±11.96, respectively. Excess lifetime cancer risk (ELCR), annual effective dose (AED), and external gamma dose rates were calculated using the average concentrations. According to the results, the overall dose gradually drops from roughly 4.0×10^{-2} to 2.2×10^{-1} mSv y^{-1}, mostly as a result of the decrease in the ^{40}K contribution. However, long-term exposure is dominated by ^{226}Ra, which stays relatively steady, whereas ^{232}Th gradually increases until stabilizing. According to the pathway analysis, ingestion pathways, especially fish intake, contribute very little but gradually grow over time, whereas external exposure from contaminated soil accounts for over 85–90% of the overall dose. Low radiological hazard is shown by the calculated dose values, which are far lower than the recommended public exposure limit of 1 mSv y^{-1} and the global average of 0.07 mSv y^{-1}. However, the persistence of long-lived radionuclides indicates continual low-level exposure, emphasizing the need for constant monitoring and efficient radiation protective measures.

INTRODUCTION

In Nigeria, artisanal and small-scale mining (ASM) has grown in popularity and involves individuals from all socioeconomic backgrounds, including local businesses and communities. The majority of mining in Niger State, especially in the Kataeregi region of Katcha Local Government Area, is done by locals using ASM techniques. ASM is distinguished by the extraction of mineral resources using simple, frequently rudimentary methods that rely on manual labour and basic equipment rather than large machinery. Millions of people and their families in resource rich areas have benefited greatly from ASM during the past few decades (World Bank, 2013; Idris-Nda et al., 2018). Government attempts to reduce ASM because of its detrimental effects on the environment and human health have mostly failed, despite its socioeconomic importance. Although ASM can create jobs and promote local development, it also has detrimental effects. By using hazardous substances like cyanide and mercury, it contaminates water sources, damages land, and upsets the natural ecology. Additionally, ASM operations may accelerate social unrest and migration in impacted areas. Minimal machinery utilization, absence of a license, low productivity, subpar safety requirements, seasonal operation, and unstable finances are common characteristics of ASM (Hentschel et al., 2002). An estimated 100 million people are directly employed by it in about 80 countries worldwide, which is far more than the roughly 7 million people who work in the industrial mining sector (World Bank, 2013). However, due to its low efficiency and informal character, ASM's contribution to the national economy is still restricted.

Naturally Occurring Radioactive Materials (NORM) like ^{226}Ra, ^{232}Th, and ^{40}K that are present in rocks and soils may become exposed and perhaps mobilized as a result of ASM mining operations that disrupt the normal geological setting. Blasting, crushing, and the use of chemicals can release these radionuclides into the environment, raising the danger of radiation exposure for miners, surrounding communities, and the ecology. The activity concentrations of radionuclides in soil, rock, and water samples from mining locations have been documented in a number of studies (Esiole et al., 2019; Muhammad & Abbasi, 2025b; Paul et al., 2022; Samson et al., 2024). Many researchers have successfully used RESRAD to evaluate the radilogical condition of mining environments worldwide. In Nigeria, Bello et al. (2022) employed RESRAD –ONSITE, RESRAD-OFFSITE, and the ERICA assessment tool to evaluate a gold mining site. They reported that the offsite doses was well within the international acceptable limits, on-site miners were exposed to annual effective dose above the recommended public limits. They suggest improvement in the radiological protection of miners and the environment. On the other hand, Njinga and Tshivhase (2018) used RESRAD-ONSITE Version 7.2 to perform radiation exposure assessment in a uranium mine tailings around the Tudor Shafi region. They found a maximum annual dose of about 1.64 $mSvyr^{-1}$ and Excess Life Cancer Risk (ELCR) above the ICRP recommended limits. They proposed that long term radiological hazards could be reduced by remediation and engineering cover. Lowson et al. (2019) used RESRAD-OFFSITE in Australia to calculate radiation dose from dust in the air during the Ranger uranium mine remediation. Their results showed that dust inhalation dose were far lower than radon-related exposures, proving the value of RESRAD in assessing long-term environmental safety during mine rehabilitation.

Similarly, in Cameroon, Gondj et al. (2022) carried out some human and ecological risk assessment in a Cobalt-nickel mining area of Lomie using the RESRAD BIOTA code. Their findings suggest that mining activities in the environment generate multiple exposure pathways to human, which would require continuous monitoring and mangement to reduce exposure. Their findings indicates that the exposure level is still within acceptable limit under the existing exposure scenarior.

More recently, Mohlomi et al. (2025) utilizes RESRAD-ONSITE and OFF-SITE to study some selected agricultural farms sorrounding mining areas in Rustenburg, South Africa. They reported that uranium isotopes has the largest proportion of the effective dose and ELCR. They concluded that the overall radiological risk for resident farmers was below the recommended international limit. The RESRAD (RESidual RADioactivity) suite of codes, developed by the U.S. Environmental Protection Agency (EPA), is a widely accepted tool for evaluating radiation dose and health risk from residual radioactivity in terrestrial environments (Yu et al., 2001). RESRAD integrates measured radionuclide concentrations with site-specific exposure parameters and considers multiple exposure pathways, including external gamma radiation, inhalation of resuspended dust, ingestion of soil, and the food chain. This capability makes RESRAD particularly suitable for assessing the potential radiological impacts of ASM activities on local communities and the environment. Therefore, this study aims to assess the radiological impact of ASM activities in the Kataeregi community by quantifying activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K and estimating the associated radiation doses (inhalation, ingestion, and external exposure) and health risks to residents using the RESRAD code.

MATERIALS AND METHODS

Study Area

The study area Kataeregi, is a small community that lies between the capital of Niger State (Minna) and the ancient city of Bida. The people of this community are usually involved in fishing, farming, and artisanal mining of gold minerals (Idris-Nda et al., 2018). The areas have a hilly relief with flat valleys in some parts. These regions typically have two distinct seasons, the rainy season and the dry season, with an average yearly rainfall of 1230 mm and an average temperature of 30°C (Odukoya et al., 2022). Reconnaissance survey was first performed to enable familiarization of the sampling sites and for easy accessibility of the study areas.

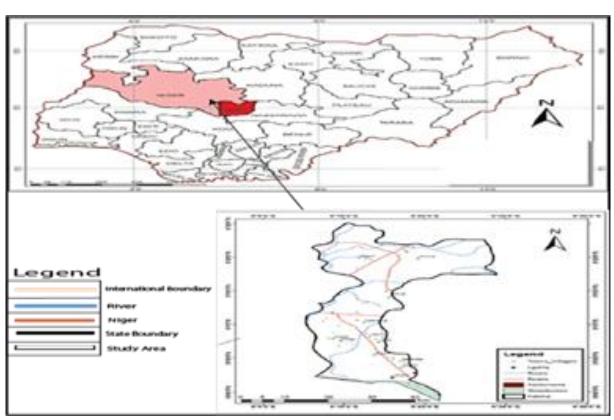

Figure 1: The Grographical Map Showing the Study Area

Sample Collection and Preparation

The American Society for Testing and Materials (ASTM) international standard for soil collection and preparation was adopted in this study. A total of 10 composite soil samples were obtained at about 1 m from the south, north, east and west of the mining hole making a square. Each soil sample was collected at about 15 cm depth and mixed thouroughly to form a composite sample. Because of the heterogenous nature of the mining holes, composite sampling was more appropriate to have an even mixture of the soil around the mining site. About 1 kg dry weight (dw) soil sample were collected at each sampling point. The samples were made into fine powder by grinding using a mortar and pestle. The soil samples were sieved through a mesh of about 1 mm size to further homogenize big grains after air-dried for 24-hours at a stable temperature of 100 ^{o}C to remove unwanted moistures.

Since mining activity naturally disturb the equilibrium of NORM in soil/rock, the daughter radionuclides with short half-lives were left to decay leaving the radionuclides of interest (^{226}Ra, ^{232}Th, and ^{40}K) to reach secular equilibrium (Muhammad & Abbasi, 2025a). Furthermore, each soil smaples were kept for 30 days in a Merinelli standard beaker (IEEE Standard, 1997; Muhammad & Abbasi, 2025a; Walley El-Dine et al., 2001).

The samples were analyzed at the radiation laboratory at Ladoke Akintola University of Technology (LAUTECH) (Nigeria) using a NaI (TI) detector with model number GS-2000 Pro multichannel analyzer with a dimension of 3 x 3 inch. Gamma-ray spectral data were acquired and analyzed using the Thermoino software. Energy calibration of the NaI(TI) detector was performed with RSS8 gamma source, Spectrum Techniques LLC, USA, using a point-like radioactive source with well define energy peaks of ^{137}Cs, ^{60}Co, ^{241}Am and ^{133}Ba. The efficiency calibration was carried out using reference materials (RGTH-1, RGU-1 and RGK-1) for the estimation of NORMs in geological materials (IAEA, 1987). After then, samples were stored for 30 days in order to attain secular equilibrium. Before counting commenced, an empty container with equal geometry as that of the detector was measured for 3600 s to obtain the background count. The sealed soil samples were each placed on the detector in succession for analysis. At this point, each soil sample was counted at equal intervals of time, as that of the empty container (3600 s), for the production of a full gamma-ray energy pack in order to determine the activity concentration in the soil. The full energy peaks of interest are ^{214}Pb (295.3 keV) and ^{214}Bi (1764.5 keV) for ^{226}Ra (^{238}U); ^{212}Pb (238.6 keV), ^{228}Ac (911.1 keV), and ^{208}Tl (2614.7 keV) for the detection of ^{232}Th, and ^{137}Cs (661.7 keV). The specific full energy peak of 1460.0 keV of ^{40}K was used to obtain its activity concentration (Muhammad & Abbasi, 2025; Oumar Bobbo et al., 2019; Ziajahromi et al., 2015). The activity concentration A of each radionuclide in the sample was calculated using equation 1:

$$A = \frac{C_{net}}{P_{\gamma} \times \varepsilon \times m \times t} \qquad (1)$$

where Pγ is the probability of gamma-ray emission, m is the mass of the soil samples, t is the counting time in seconds, ε is the efficiency of the radionuclides full energy peak, and C_{net} is the net peak count for each radionuclide in the sample after deducting the background count from the gross count (Asgharizadeh et al., 2012).

Resrad Simulation Code

This study utilizes the RESRAD offsite code to calculate the internal exposure (ingestion from soil, water, plants, and inhalation from radon gas) and external exposure (direct gamma radiation exposure emitted from soil) risk for NORM is soil for the artisanal miners and resident of the mining community (Kataeregi).

Kataeregi is dominated by gold, granite, and clay minerals, respectively. This mining area was selected because it lies within the basement complex zones, which are characterize with large deposit of gold and other valuable minerals (Idris-Nda et al., 2018).

RESRAD simulaion is widely adopted by researchers and many international organization (e.g. IAEA and ICRP) to estimate the radiation dose and residual radioactivity of the affected community (Ziajahromi et al., 2015). The average activity concentration used for the RESRAD simulation of the soil sample was taken from Table 4. The conversion dose factors for the inhalation and ingestion were derived from the ICRP 60 (Clement, 2013) and NORM transformation were adopted from the ICRP 107 report (ICRP, 2007). Default/specific site parameters (see Table 3) were adopted primarily to represent standard human and environmental behaviour, while also ensuring consistency and comparability of results across different studies and regions. The RESRAD dose estimation in this study focuses on external and internal pathways within the artisanal mining environment. However, aquatic food pathways were ignored because most of the aquatic food items consume by the residents of the mining environments are directly bought from the market and has no direct contact with the mining sites.

Therefore, the scenarior area considered has a total size of 12,000 m^2 as shown in Table 3. All site-specific information used in the RESRAD calculation were taken from the default values, except the contaminated zone, inhalation rate, exposure to gamma radiation rate, and soil ingestion rate, respectively (see Table 2) (Yu, 2012). Table 1 shows the location and type of minerals mined in the study area.

Table 1: Mineral Mines in the Study Areas and Their Geographical Locations

Sample ID	Location	Minerals processed	On-Site/Off-site	COORDINATES LATITUDE	COORDINATES LONGITUDE
15	Kataeregi	Gold, Clay and Kaolin	Off-site	09º42'50.5"	006º45'37.1"
16	Kataeregi	Gold, Clay and Kaolin	On-site	09º42'48.6"	006º45'36.9"
17	Kataeregi	Gold, Coal and Baryte	On-site	09º22'50.6"	006º19'38.3"
18	Kataeregi	Gold, Coal and Baryte	Off-site	09º 22'51.2"	006º19'39.6"
19	Kataeregi	Gold, Coal and Baryte	On-site	09º22'51.2"	006º19'41.1"
20	Kataeregi	Gold, Coal and Baryte	Off-site	09º22'52.7"	006º19'42.4"
21	Kataeregi	Gold, Coal and Baryte	Off-site	09º22'53.7"	006º19'43.8"
22	Kataeregi	Gold, Coal and Baryte	Off-site	09º22'54.3"	006º19'45.3"
23	Kataeregi	Gold, Coal and Baryte	Off-site	09º22'55.5"	006º19'46.5"
24	Kataeregi	Gold, Coal and Baryte	On-site	09º22'56.2"	006º19'47.8"

Table 2: Risk Coefficient for Cancer Morbidity Used in the RESRAD Database (Yu et al., 1993)

	Risk Coefficient for Cancer Morbidity		
Radionuclide	Inhalation (Bq^{-1})	Ingestion (Bq^{-1})	External (1/yr)/(Bq/g)
^{210}Bi	7.21×10^{-12}	1.30×10^{-4}	8.92×10^{-12}
^{212}Bi	1.37×10^{-12}	-	-
^{214}Bi	5.55×10^{-13}	-	-
^{40}K	2.78×10^{-13}	4.81×10^{-13}	2.26×10^{-8}
^{210}Pb	6.29×10^{-11}	2.52×10^{-11}	4.07×10^{-12}
^{212}Pb	1.44×10^{-12}	-	-
^{214}Pb	2.29×10^{-13}	-	-
^{210}Po	7.77×10^{-11}	1.22×10^{-11}	1.22×10^{-12}
^{218}Po	1.37×10^{-13}	-	-
^{224}Ra	1.44×10^{-10}	2.37×10^{-10}	1.66×10^{-10}
^{226}Ra	1.04×10^{-10}	1.11×10^{-11}	2.48×10^{-7}
^{228}Ra	3.66×10^{-11}	9.25×10^{-12}	1.22×10^{-7}
^{220}Rn	7.03×10^{-15}	-	-
^{222}Rn	6.66×10^{-14}	-	-
^{228}Th	3.59×10^{-9}	8.51×10^{-12}	2.29×10^{-7}
^{230}Th	6.29×10^{-10}	1.41×10^{-12}	1.63×10^{-12}
^{232}Th	7.03×10^{-10}	1.22×10^{-12}	7.4×10^{-13}
^{234}Th	6.92×10^{-11}	1.32×10^{-11}	8.32×10^{-12}
^{234}U	5.18×10^{-10}	1.63×10^{-12}	7.77×10^{-13}
^{238}U	4.44×10^{-10}	2.29×10^{-12}	2.44×10^{-09}

Table 3: Site-Specific Parameters of the Areas Under Study

Parameters	Site-Specific Data
Contaminated zone Area	15,000 m^2
Thickness of uncontaminated zone	4 m
Thickness of soil	2 m
Total porosity of saturated zone	0.4
Dry bulk density of saturated zone	1.5 grams/cm^3
Effective porosity of saturated zone	0.2
Hydraulic conductivity of saturated zone	10 m/year
Soil specific exponential b parameter	5.3
Erosion rate	0.001 m/year
Water table drop rate	0.001 m/year
Inhalation rate	15 m^3/day
Exposure rate	14 hr/day
Soil ingestion rate	26 mg/day

RESULTS AND DISCUSSION

The results for the average activity concentrations is shown in Table 4. ^{40}K (360.13± 11.96 BqKg^{-1}) has the highest acivity concetration followed by ^{226}Ra (18.74±0.8 Bq Kg^{-1}), and ^{232}Th (9.12± 1.23 Bq Kg^{-1}) in the order $^{40}K>^{226}Ra>^{232}Th$, respectively. The highest average activity concentration of ^{40}K could have resulted due to intense use of fertilizer by farmers to improve farm yield as well as the large deposit of granite rocks in the study area.

The average concentrations of NORM in the soil samples shown in Table 4 was used as input in RESRAD simulation code to estimate the morbidity excess cancer risk for the artisanal miners and residents of the mining community. In the RESRAD simulation code, the default parameters (see Table 3) used were define as well as the measured parameters. Therefore, the artisanal miners have the highest risk of cancer compared to residents outside the active mining area within the community. The different radionuclide risk coefficient for cancer morbidity is shown in Table 2.

Table 4: The Activity Concentration of ^{226}Ra, ^{232}Th and ^{40}K in Soil Samples of Study Area

Sample ID	Activity concentration (Bq kg^{-1}) ^{226}Ra	^{232}Th	^{40}K
E1	27.56 ± 1.18	8.59 ± 1.90	403.49 ± 9.39
E2	23.21 ± 1.93	6.97 ± 1.10	447.40± 12.67
E3	24.69 ± 1.12	9.31 ± 1.98	361.44± 10.29
E4	16.25 ± 0.57	10.07 ± 1.10	356.10± 12.39
E5	18.24 ± 0.61	10.42 ± 1.12	373.72± 10.98
E6	13.72 ± 0.53	12.07 ± 1.20	359.59± 12.09
E7	11.87 ± 0.49	9.90 ± 1.09	337.70± 14.15
E8	16.19 ± 0.57	10.04 ± 1.10	321.88± 15.95
E9	18.01 ± 0.34	6.74 ± 0.74	341.95± 13.02
E10	17.70 ± 0.38	7.10 ± 0.97	298.05 ± 8.71
Min.	11.87 ± 0.49	3.50 ± 1.21	256.76 ± 6.56
Max.	27.56 ± 1.18	12.07 ± 1.20	447.40± 12.67
Mean	18.74±0.8	9.12± 1.23	360.13± 11.96

Table 5: Comparison of Published RESRAD Studies on Some Selected Mining Environment Around the World

Study	^{238}U (Bq/kg)	^{226}Ra (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)	Annual Effective Dose (mSv y^{-1})
Bello et al. (2022)	Site specific	Site specific	Site specific	Site specific	>1.0 (on-site); <1.0 (off-site)
Njinga & Tshivhase (2018)	>100	~120	-	-	1.64
Gondji et al. (2022)	30–80	20–60	25–70	200–500	<1.0
Mkwelo et al. (2020)	Model input	Model input	Not primary	Not primary	<1.0
Lowson et al. (2019)	Waste-rock specific	Associated with U-series	-	-	<1.0
This study	Site specific	18.74	9.12	360.13	0.112
World Average (UNSCEAR, 2008)	35	35	30	400	0.07

The results presented in Table 5 show that the annual effective dose for the offsite scenario is less than 1 mSv y^{-1}, whereas the annual effective dose for the onsite scenario exceeds 1 mSv y^{-1}. These findings indicate that the NORM concentrations at the mining sites are generally below the global average, particularly in the offsite areas. Furthermore, the average activity concentrations of all measured radionuclides are below the recommended limits reported by UNSCEAR.

The results shown in Figure 2(A) indicates that the total radiation dose gradually decreases over time, from approximately 4.0×10^{-4} mSv y^{-1} to 2.6×10^{-4} mSv y^{-1} after 100 years. Initially, ^{40}K is the dominant contributor but declines significantly with time. On the other hand, ^{226}Ra remains relatively constant and becomes the primary contributor in the long term, while ^{232}Th increases and stabilizes, contributing significantly to the constant dose levels.

Furthermore, the results in Figure 2(B) indicates that the total dose from ^{232}Th increases significantly over time due to progeny ingrowth, reaching approximately 1.05×10^{-4} mSv y^{-1} at 100 years. ^{228}Th is the dominant contributor, accounting for over 50% of the total dose, followed by ^{228}Ra. The parent radionuclide (^{232}Th)

contributes negligibly. This indicates that decay products, not the parent radionuclide, are the main factor influencing long-term radiation hazard. As a result, Figures 2(A) and 2(B) show that radiation exposure in artisanal mining settings is time-dependent. Long-term exposure is controlled by ^{226}Ra and the ingrowth of ^{232}Th progeny, whereas short-term exposure is dominated by ^{40}K and diminishes over time. Eventually, the system achieves secular equilibrium, which produces a radiation dose that is comparatively stable but persistent. These results emphasize the significance of taking progeny ingrowth and radioactive degradation into account when evaluating long-term radiological hazard.

Figure 3 shows that direct radiation from soil is the dominant exposure pathway, contributing over 85% of the total dose throughout the study period. The total dose decreases from approximately 4.1 × 10^{-4} mSv y^{-1} to 2.2 × 10^{-4} mSv y^{-1} over 100 years. Ingestion pathways show a gradual increase but remain relatively minor contributor. Other pathways such as drinking water, plant, meat, and radon exposure contribute negligibly to the overall dose. Furthermore, the low dose obtained from radon by the simulation clearly shows that radon was not analyzed in this study due to limited time of sample transfer to the research laboratory.

Figure 4 show the water dependent and dependent subtotal. It can be observed that majority of the radionuclide have migrated through the water bodies within the study areas, thereby causing contamination of the agricultural farmland and other resourceful sources of water. The migration of the radionuclide is expected to drop during the dry season when the run-off water have dried. Therefore, there is a temporal dependence of migration of radionuclide due to seasonal change in the study area. Furthermore, Figure 5 show that the excess cancer risk is influenced by the rate of migration of radionuclide. It can be seen that high migration rate of radionuclides leads to increase in the cancer risk due to high ingestion rate in water.

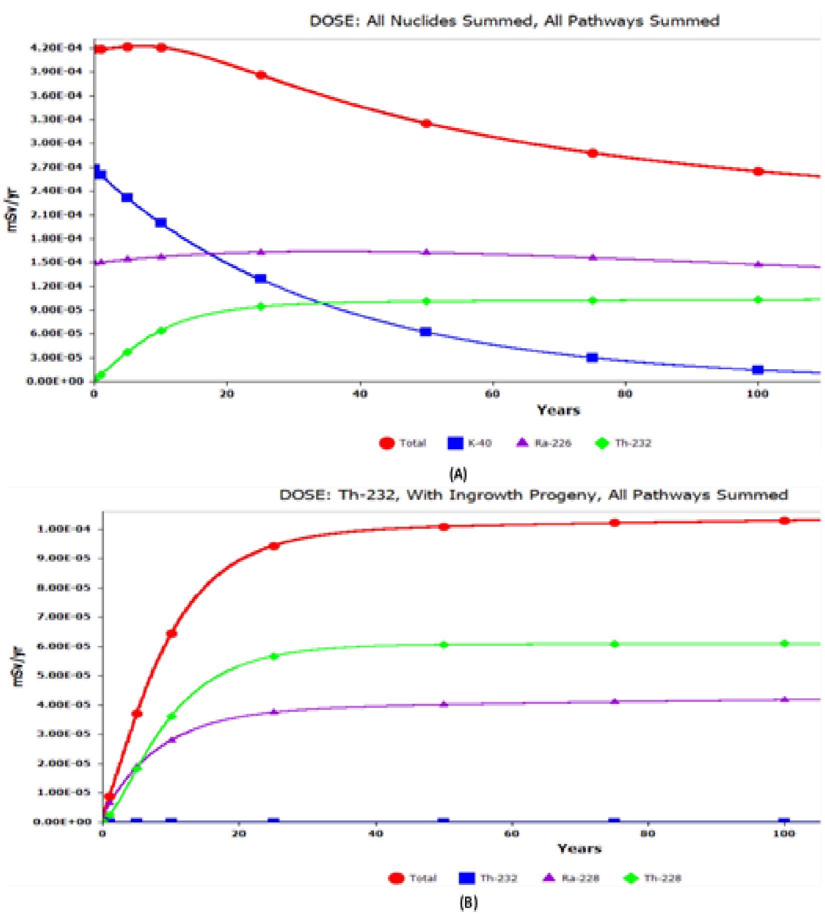

Figure 2: Variation of Dose over Time with 232Th Progeny

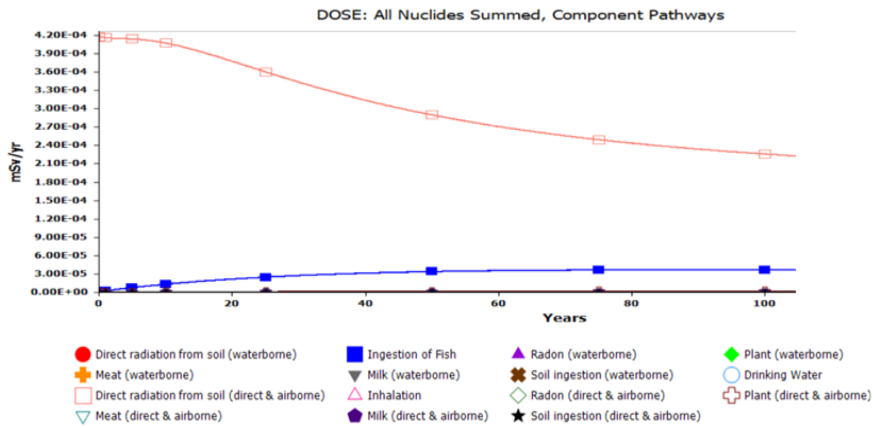

Figure 3: All Nuclides Summed, Component Pathways

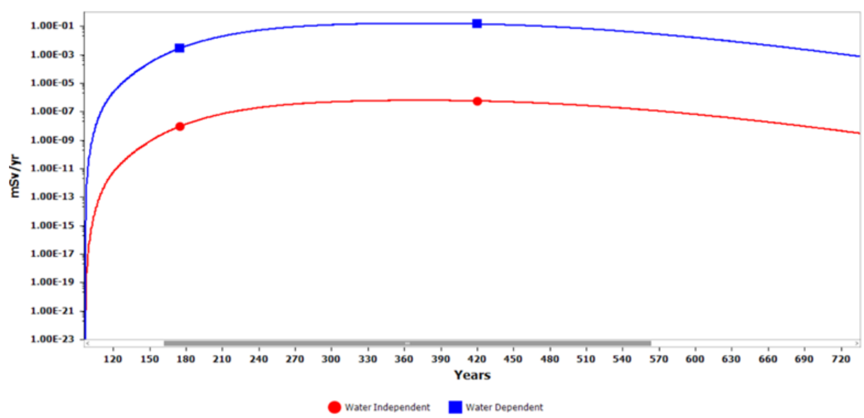

Figure 4: Dose, Water Independent and Dependent Subtotal

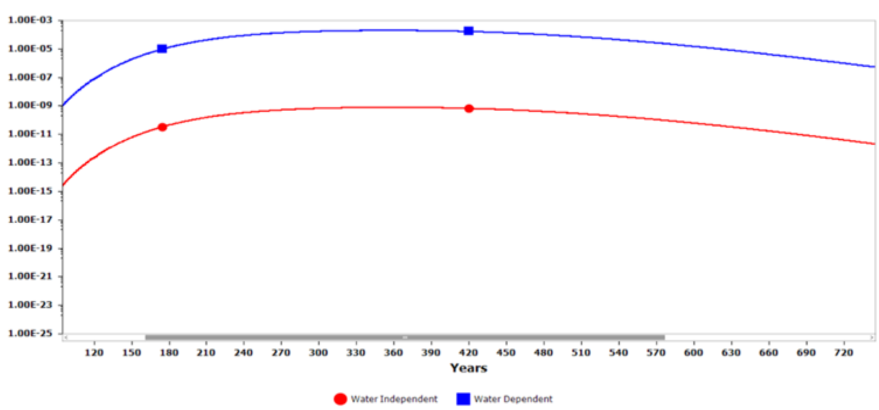

Figure 5: Excess Cancer Risk- Water Independent and Dependent Subtotals

In Figure 6, the ELCR values decrease from approximately 9.5×10^{-7} to 5.5×10^{-7} over 100 years, primarily due to the rapid reduction in ^{40}K. However, ^{226}Ra remains a dominant contributor, while ^{232}Th increases from about 1.5×10^{-7} to 2.4×10^{-7} due to progeny ingrowth. This result in a sustained long-term cancer risk despite the overall declining trend.

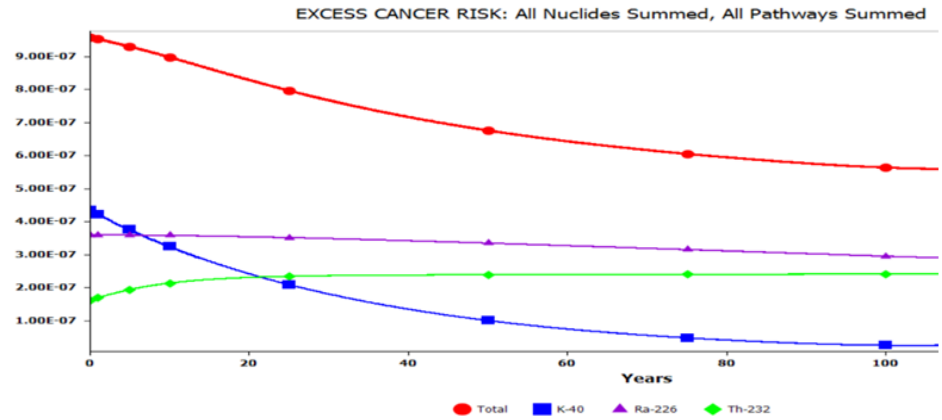

Figure 6: Excess Cancer Risk: All Nuclide Summed, All Pathways Summed

Different radiological behaviors across the exposure period were identified by comparing the excess cancer risk (ECR) for ^{40}K, ^{232}Th, and ^{226}Ra, respectively (see Figure 7). With ECR values falling exponentially over a 100-year period from 4.20×10^{-7} to 3.00×10^{-8}, the ^{40}K graph showed a clear downward trend, suggesting a significant decrease in radiological risk over time. ^{226}Ra similarly showed a declining trend, but it was more gradual, with ECR values falling from 3.60×10^{-7} to 2.92×10^{-7}. Furthermore, the excess cancer risk for ^{232}Th showed an increasing pattern, growing quickly in the early exposure period before settling at about 2.40×10^{-7}. Out of the three radionuclides examined, ^{40}K had the highest ECR value at first, but decreases with time, resulting in the lowest long-term risk. While ^{232}Th demonstrated progressive risk buildup prior to reaching equilibrium and ^{226}Ra stays with comparatively higher ECR values throughout the exposure time despite its gradual decline. In general, all predicted ECR values stayed within the order of 10^{-7}, indicating minimal radiological health risks within the research area.

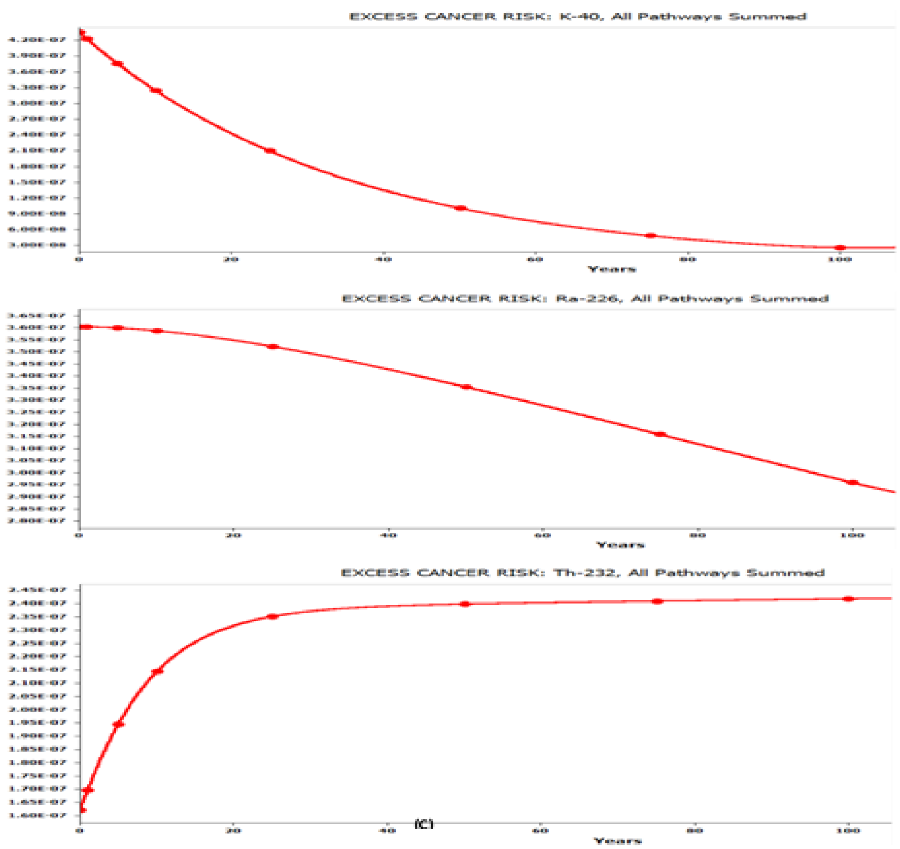

Figure 7: Excess Cancer Risk: All Pathways Summed

CONCLUSION

The results show that external gamma radiation from soil in Kataeregi artisanal mining site is the dominant source of radiation exposure, contributing over 85–90% of the total dose. The total dose decreases over time (4.1×10^{-4}–2.2×10^{-4} mSv y^{-1}), leading to rapid reduction of ^{40}K. The estimated dose values are significantly lower than the global average outdoor exposure of 0.07 mSv y^{-1} reported by UNSCEAR and well below the recommended public dose limit of 1 mSv y^{-1} set by the ICRP, respectively. The corresponding excess lifetime cancer risk falls within international acceptable limits, indicating minimal radiological health risk. However, the persistence of long-lived radionuclides such as ^{226}Ra and ^{232}Th suggests the need for continued environmental monitoring and assessment. Among exposure pathways, direct radiation from soil dominates, while ingestion pathways remain minor. Other pathways are negligible.

In general, even though radiation levels decline, persistent low-level exposure remains over a long period, highlighting the importance of ongoing monitoring and radiation protection in Kataeregi artisanal mining area in Niger State and environs.

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